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Evaluation of erosion control geotextiles on steep slopes. Part 1: Effects on runoff and soil loss

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ABSTRACT

Geotextiles have been demonstrated to be effective in reducing erosion and subsequent slope degradation processes. However, most studies devoted to assessing the effectiveness of those elements have considered small or intermediate slope gradients (normally ≤30°), whereas real engineering works often lead to steeper slopes needing protection. In addition, although a large amount of laboratory studies exist on this topic, there are few articles reporting field experiments which consider large plots, real precipitation and prolonged study periods. This paper is the first of two in which the performance of erosion control geotextiles on steep slopes (45° and 60°) has been assessed. In this paper, the influence of geotextiles on runoff and soil loss reduction was evaluated. The second paper focuses on the effects of geotextiles on the establishment and growth of vegetation on the slope. The research was carried out on an experimental embankment built in Pamplona (Spain) following standard construction procedures in order to resemble real engineering slopes. Two biological geotextiles (jute net and coir blanket) and a synthetic polyester geogrid, installed in two positions (surface-laid and buried), were evaluated and compared with a vegetated hydroseeded control plot. After each significant rain event, runoff and soil loss amounts produced on each plot were recorded. The results showed that coir and jute geotextiles produced 2–3 times larger runoff volumes than the control plots on both the 45° and 60° slopes, whereas the synthetic geogrid did not give significantly different runoff rates from the control (at $p < 0.05$). Geotextiles were more effective in reducing soil loss at 45° than at 60°. The most effective treatment was the surface-laid geogrid, with a median Soil Loss Reduction Effectiveness (SLRE) of 76% and 53% for the 45° and the 60° slopes, respectively. At 45° the coir blanket showed lower soil losses than the control (median SLRE of 61%), but at 60° its protection action was more irregular (median SLRE of only 8%). The jute net and the buried geogrid produced lower erosion rates (median soil loss of 3.2 g m^{-2} and 2.1 g m^{-2}, respectively) than the control (median soil loss of 3.6 g m^{-2}) at 45°, but at 60° the erosion rates observed were similar to those of the control. In short, the surface-laid geogrid produced the lowest soil loss rates. However, when buried, the geogrid did not effectively control erosion, at least not that of the upper soil layer. Thus, its surface installation seems to be a better option. In cases where burial is preferred for aesthetic reasons (i.e. hiding the geogrid), a higher soil loss must be assumed.

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1. Introduction

Civil engineering projects often lead to disturbed, bare soils with steep slopes, which are very sensitive to runoff and soil loss processes. The degradation of those slopes causes severe impacts onsite (e.g. reduced soil structure and water holding capacity resulting in lower fertility) (Cerdá, 2007) and offsite (e.g. malfunction of gutters and drains affecting road conservation and safety, turbidity and siltation of water courses) (Morgan, 2005; Owens et al., 2005), so that the design and implementation of erosion control measures is crucial in any project of this kind.

One of the most used control measures is the placement of geotextiles over sloping surfaces (Rickson, 1995). Geotextiles are nets or mats which protect the soil and reduce the detachment and transport capacity of rainfall and overland flow. Ideally, they should also promote vegetation growth, due to their enhanced soil and water holding capacity. Their protection mechanism is therefore expected to be twofold: first, through their direct protection of the soil surface against eroding agents, and second, through benefits in the development of a dense protective vegetation cover.

Several physical properties of geotextiles have proven to be vital for soil protection. Specifically, the fraction of open area (or the relative size of apertures), moisture sorption depth, mat thickness, hydraulic roughness and tensile strength are key properties controlling the performance of such materials in each particular

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setting (Rickson, 2006). Additionally, the erosion reduction capacity of a geotextile will also vary depending on slope length and gradient, soil type and local precipitation regime (Bhattacharyya et al., 2010).

Geotextiles are normally made of permeable materials which can be either biological or synthetic. The former are mainly made from natural fibres (i.e., jute, coir or palm). Synthetic geotextiles are normally made of polymers (i.e., polyester, polypropylene or polyolefin). The cost of synthetic geotextiles is significantly higher than that of biological materials. However, the performance of a geotextile is related to its physical properties (mentioned above) which are much more important than the geotextile material itself (Ziegler et al., 1997). Synthetic geotextiles offer stronger reinforcing action (i.e. higher tensile strength) and last longer (≥20 years) than natural fibres (~2–5 years) (Li and Khanna, 2008). In turn, the degradation of biological geotextiles (contributing organic matter and nutrients to the soil) could be beneficial for the development of vegetation on slopes, which may play a key role as a long term erosion protection measure (Fullen et al., 2011).

Several comprehensive reviews focusing on the influence of different factors and geotextile properties on their performance have been published previously (Bhattacharyya et al., 2010; Rickson, 2006; Sutherland, 1998a, 1998b). Bhattacharyya et al. (2010) considered that three separate erosion types (rainsplash, interrill and rill–interrill erosion) depended on the length of slopes to be protected, and they summarised the results of many laboratory and field experiments. Most experiments reported by Bhattacharyya et al. (2010) confirmed the effectiveness of geotextiles for reducing runoff, obtaining similar results with both synthetic and biological geotextiles. Their analyses also highlighted the role of geotextiles in reducing the impact of splash erosion behaving as a physical barrier, which dissipated the kinetic energy of raindrops and their erosivity. Accordingly, the area cover fraction was identified as a key property for erosion reduction.

Characteristics of slopes to be protected are also crucial for the adequate performance of geotextiles. As already mentioned, slope length and gradient are particularly important properties which influence, and even sometimes determine, the type of erosion process occurring. Long and steep slopes usually lead to higher energy runoff with a stronger sediment detachment and transport capacity (Smets et al., 2007). However, steeper slopes do not necessarily have lower infiltration rates since other factors (such as surface roughness and sealing) can affect infiltration on them (Assouline and Ben-Hur, 2006). The protective action of a geotextile might also vary depending on the length and gradient of the slope to be protected. Some authors observed better soil contact (and hence more effective protection) on short slopes than on long ones, where void spaces could cause preferential flow paths underneath the geotextile (Chen et al., 2011). In short, care should be taken when extrapolating results on the effectiveness of geotextiles from low and medium slopes to steep slopes (Chen et al., 2011; Ogbobe et al., 1998; Smets et al., 2007).

Most experiments assessing the protective action of geotextiles have been carried out in laboratory settings using rainfall simulators and considering reduced plot dimensions and slope gradients (Bhattacharyya et al., 2010). Outdoor experiments on this topic are scarce, particularly those considering long time periods. Although laboratory experiments provide valuable information on the processes and factors involved, the conditions tested in these settings might not entirely represent real field conditions (Smets et al., 2011). In fact, soil properties (moisture, texture, structure, depth, and profile) and rainfall characteristics (intensity, duration, depth, kinetic energy, and water quality) can be significantly different (Smets et al., 2011). As a result, it is necessary to further extend research activities in this topic to more realistic conditions, where longer and steeper slopes are examined under natural precipitation.

In this study, the performance of erosion control geotextiles on steep slopes (45° and 60°) is evaluated under natural conditions. With this aim, an experimental embankment was constructed following standard construction practices. The focus of the study is to assess the influence of geotextiles on runoff and soil loss reduction.

2. Materials and methods

2.1. Experimental setting

The experiment was carried out in the experimental fields of the School of Agricultural Engineering of the Public University of Navarre in Pamplona (Spain). Its geographical coordinates are: 42°47′39″N, 1°37′52″W, and it is 435 m above sea level. The climate is humid sub-Mediterranean with annual precipitation of ~800 mm and a mean temperature of ~12 °C. The precipitation regime is strongly seasonal, with dry summers with short, intense convective storms and longer front-like events during the rest of the year. The soils are silty–clay–loam in texture (sand = 13.8%; silt = 53.9%; clay = 32.3% and organic matter = 1.8%) with significant silt and low organic matter proportions and, hence, they are highly erodible.

An experimental embankment was constructed following standard construction practices. The use of an outdoor experimental setting makes it possible to reproduce an engineered slope with fixed characteristics (gradient, length or soil type) more realistically and is the most convenient choice for medium to long term experiments with natural precipitation events and vegetation dynamics. However, one drawback is that the continuous measurement of hydrological variables (infiltration, overland flow and sediment concentration) is more difficult than in laboratory plots.

The material used in the earthwork operations was the same soil present on the site, which was mechanically compacted (layer by layer) using a smooth steel-wheel roller, in order to reproduce 'real' earthworks as far as possible. The final mean bulk density at the soil surface was 1.57 Mg m^{-3} (n = 20, SD = 0.1), which corresponds to a significantly compacted soil. The local undisturbed soil had a mean bulk density of ~1.34 Mg m^{-3}. The orientation of the embankment was east and its total width was 50 m. It was divided into two sections with different slope gradients, 45° and 60°, and an intermediate transition area. Five different geotextile treatments were created on each section (each treatment had three replicates) making a total of 30 plots, each 1.3 m wide. The embankment reached a height of ~4.5 m above its base. The first 1.5 m was required to install flow collecting gutters and tanks and the remaining 3 m were used for the experiment, resulting in a final length for the experimental plots of 4.1–4.6 m for the 45° slope and 3.4–3.8 m for the 60° slope. A detailed topographic survey was used to obtain the exact dimensions of each plot (Table 1). The different sizes of the 60° plots (~7.5 m^2) and 45° plots (~13 m^2) need to be taken into account when comparing the results of the two datasets. The top of the embankment was sealed with plastic and a crossfall of 3–5% was placed towards the rear in order to avoid overland flow into the slope and to reduce infiltration through the embankment.

The experimental slope was hydroseeded on 11 May 2009 using a seed mixture with species adapted to local climate conditions, mainly grasses (~70%) and legumes (~25%) (Alvarez-Mozos et al., submitted for publication). The seeding rate was 70 g m^{-2}. Due to logistic constraints, the seeding was performed outside the recommended seeding period. Therefore, in order to ensure adequate germination, a sprinkler irrigation system was installed, which was switched on

Table 1
Plot size (m^2) for each treatment and slope gradient.

	Jute net	Coir blanket	Geogrid[a]	Geogrid (B)[b]	Control
60° slope	7.86	7.53	7.34	7.66	7.57
45° slope	13.05	13.58	13.79	12.84	12.95

[a] Surface laid.
[b] Buried.

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